Proactive Spraying Against Boll Weevils (Coleoptera: Curculionidae) Reduces Insecticide Applications and Increases Cotton Yield and Economic Return

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ABSTRACT The current standard practice of two to three preemptive insecticide applications at the start of pinhead (1–2-mm-diameter) squaring followed by threshold-triggered (whenever 10% of randomly selected squares have oviposition punctures) insecticide applications for boll weevil, *Anthonomus grandis grandis* Boheman, control does not provide a reliably positive impact on cotton, *Gossypium hirsutum* L., yields in subtropical conditions. This study showed that four fewer spray applications in a "proactive" approach, where spraying began at the start of large (5.5–8-mm-diameter) square formation and continued at 7- to 8-d intervals while large squares were abundant, resulted in fewer infested squares and 46–56% more yield than the standard treatment at two locations during 2004. The combination of fewer sprays and increased yield made the proactive approach 115–130% more profitable than the standard. The proactive approach entails protection only at the crop's most vulnerable stage (large squares) that, as a source of food, accelerates boll weevil reproduction. In contrast, the standard approach protects early season small squares and later season bolls, both of which contribute less to boll weevil reproduction than large squares. Proaction is an in-season crop protection approach that can be used to increase yield in individual fields during the same season and that could be incorporated into boll weevil eradication strategy that involves later diapause sprays. Because proaction is based on an important relationship between the cotton plant and boll weevil reproduction, the tactic will probably be effective regardless of climate or region.

KEY WORDS boll weevil, cotton, insecticide, proactive, threshold

THE BOLL WEEVIL, *Anthonomus grandis grandis* Boheman, is originally from the tropics and subtropics of Mesoamerica (Burke et al. 1986). Its present distribution extends from the U.S. Cotton Belt to Brazil and Argentina (Ramalho and Jesus 1988, Cuadrado 2002), but studies on control tactics have largely been limited to the temperate United States and the subtropical Lower Rio Grande Valley of Texas. Preemptive insecticide application for boll weevil control in cotton, *Gossypium hirsutum* L., as practiced in the Lower Rio Grande Valley, involves spraying when the first pinhead-sized (1–2-mm-diameter) squares are formed followed by one to two additional applications 3–5 d apart (Heilman et al. 1979, Showler 2004a), and early sprays also have occurred in other states, some triggered by pheromone-based trap captures (Knipling 1979, Ridgeway et al. 1983, King et al. 1996). In the subtropics, where boll weevil populations are active year-round (Guerra 1986), Heilman et al. (1979) suggested that preemptive spraying might delay the late season insecticide applications, but other research found no beneficial effect (Showler 2004a) and economic rationale is debatable. After that, insecticide applications are triggered whenever 10% of randomly selected squares have oviposition punctures (Showler et al. 2005). This occurs when bolls, less susceptible to weevil damage (Stewart and Sterling 1989), become the predominant fruiting stage (Showler et al. 2005).

Boll weevils prefer to feed and oviposit on large (5.5–8-mm-diameter) squares more than on pinhead and match-head (2–3-mm-diameter) squares, and fecundity and oviposition accelerate when females feed on large squares instead of match-head squares and bolls of any age (Showler 2004b, 2005). Although preemptive sprays might kill some adult boll weevils that have entered the field, the sparse numbers of weevils and the presence of less-preferred and nutritionally inferior small squares contribute relatively little to field-level population buildups and have negligible impact on lint yield (Showler 2004a, Showler et al. 2005). The purpose of this study was to assess the effects of applying insecticide only while squares are

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large on boll weevil infestation, lint yield, and net economic return.

Materials and Methods

Separate field experiments were conducted at the USDA–ARS Kika de la Garza Subtropical Agricultural Research Center (KSARC) and ≈3 km south at the KSARC annex called Ansul, Hidalgo County, Texas, during 2004. At KSARC, a 1.8-ha experimental research field planted to cotton (variety DP5415RR) on 2 March 2004 was divided into fifteen 0.12-ha plots, each 16 rows (1-m row spacing) in width by 160 m in length. At Ansul, a 1.9-ha experimental field planted with the same variety on the same day also was divided into 15 plots. The early March planting date was chosen because it was shown to be optimal in Hidalgo County for net economic returns (Showler et al. 2005). Pendimethalin (Prowl, 3.3 EC, BASF, Florham, NJ) at 924 g ([AI])/ha was applied by tractor immediately after planting, and weed control was thereafter conducted with a rolling cultivator or by hand-roguing. Irrigation occurred at the start of bloom (mid-May).

Three treatments were arranged in a randomized complete block design at both locations. Five plots at each location were treated with the "standard" spray approach whereby three preemptive insecticide sprays were applied on 16, 20, and 23 April. The plots were scouted every 2 d thereafter, and an insecticide application was triggered whenever 10% of 50 randomly checked squares had oviposition punctures. Infestations in each standard treatment plot reached 10 ± 1.2% at the same times, and in each instance cyfluthrin was applied at a rate of 45 g ([AI])/ha through 16 Teejet 8003E nozzles, two angled toward each row, at a pressure of 3.5 kg/cm^3 (1.6 liters/min/nozzle) on a tractor boom on 20, 25, and 29 May and 3, 15, and 22 June. In the "proactive" treatment, five plots at each location were treated with cyfluthrin on 11 May, when ≈2% of the squares had become large, even though adult boll weevils occur in cotton fields before large squares are formed (Showler 2005) and automatically at approximately weekly intervals thereafter, regardless of levels of boll weevil infestation, on 18 and 25 May and 3 and 11 June. The five control plots at each location were not treated with insecticides. No other pesticides were needed for arthropod control throughout the study because other herbivorous arthropod populations did not increase to economically threatening levels.

Numbers of squares and bolls, and numbers of each with oviposition and feeding punctures, in one randomly selected 1-m section of row per plot were counted on 21 April, 5 and 19 May, and 2 and 16 June. Twenty-five randomly selected plants per plot were sampled for adult boll weevils using a beat bucket (Knutson and Wilson 1999, Knutson et al. 2000) on the same dates. Numbers of plants in two separate randomly selected 1-m sections of row per plot, and heights of 25 randomly selected plants in each plot, were recorded on 19 April (start of pinhead development) and 19 May (large squares predominant). Fallen bolls were counted along three randomly selected 5-m sections of row in each plot.

The fields were defoliated using S,S,S-tributylphosphorotrithioate at 1.6 kg ([AI])/ha on 14 July. Cotton was hand harvested from two randomly selected 4-m sections of row in each plot on six and 14 July. One block of harvested cotton for KSARC was lost; hence, only four replicates were used in the analysis of yield for that location. Seed cotton and ginned lint weights were recorded.

Partial budgeting analysis of the treatments and two additional hypothetical scenarios was conducted by adapting extension planning budgets for irrigated cotton (Robinson 2004). Gross income was calculated by applying a price of \$1.15/kg to the yield data. Harvest costs were deducted using a value of \$0.44/kg for custom picking, hauling, and ginning. Net returns comparisons of the treatments were then derived by using the following costs: \$14.83/ha for one treatment of cyfluthrin (chemical only), \$4.14/ha for a ground application, and \$6.61/ha for an aerial application.

Three scenarios of treatment comparisons are made in this study. Scenario 1 represents the yield data, harvest costs, and chemical and application costs of the treatments as they actually occurred (nine ground applications of cyfluthrin in the standard treatment). Scenario 2 represents a likely situation where the final

Table 1. Mean (± SE) cotton plant densities and heights at two locations during the start of pinhead square development on 21 April, and on 19 May when large squares were predominant, 2004, Hidalgo County, Texas

Location[a]	Treatment	19 April		19 May	
		Density per m row[b]	Height cm[c]	Density per m row[b]	Height cm[c]
KSARC	Control	36.2 ± 1.8	28.6 ± 1.4	29.8 ± 1.2	65.0 ± 2.7
	Standard	35.8 ± 2.0	30.4 ± 1.1	28.7 ± 2.1	64.0 ± 3.9
	Proactive	35.0 ± 1.8	31.0 ± 0.7	30.5 ± 1.5	69.0 ± 1.6
Ansul	Control	39.6 ± 0.4	27.8 ± 0.5	32.3 ± 1.3	66.0 ± 1.2
	Standard	37.6 ± 1.3	28.2 ± 0.4	33.3 ± 2.7	64.8 ± 1.0
	Proactive	38.8 ± 0.7	28.0 ± 0.9	30.8 ± 1.2	63.0 ± 1.6

Significant differences ($P < 0.05$) were not detected within the same column and location, ANOVA.
[a] USDA–ARS experimental field sites ≈2 km apart.
[b] n = two separate, randomly selected 1-m sections of row were sampled in each plot.
[c] n = 25 plants/plot.

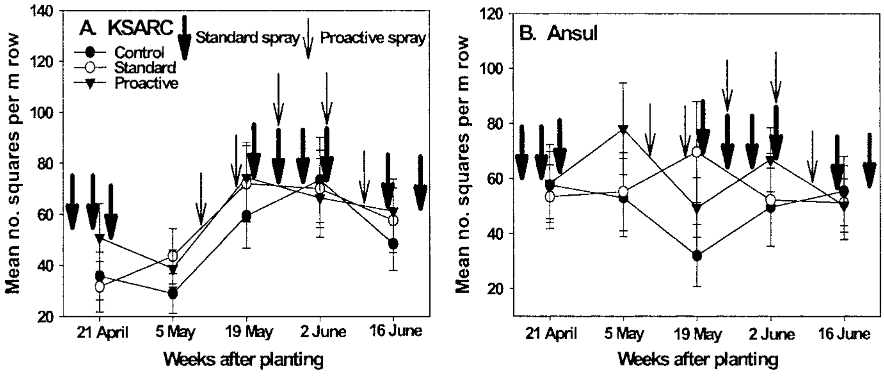

Fig. 1. Mean (±SE) numbers of squares per meter of row in nontreated control plots and in standard and proactive insecticide treatment plots at KSARC (A) and Ansul, Hidalgo County, Texas (B), 2004 (n = 5).

two applications of scenario 1 are made by aircraft. Scenario 3 reflects the possibility that two additional aerial applications, as commonly occur, are applied late in the season. The control and proactive treatments are the same under all three scenarios.

Plant densities and heights; numbers of squares, oviposition-punctured squares, and bolls per meter of row; and numbers of boll weevils collected in beat buckets were $\log(x + 1)$ transformed to ensure normality of the data and analyzed using repeated measures analysis of variance (ANOVA) (Analytical Software 1998). Yields and economic returns were $\log(x + 1)$ transformed and analyzed with one-way ANOVA and means were separated using Tukey's honestly significant difference (Analytical Software 1998). The study was conducted at two locations during 1 yr because during the following year, 2005, the boll weevil eradication program (Dickerson et al. 2001) began, and this involved mandatory applications of malathion on a schedule different than the standard or proactive approaches.

Results

Treatment effects were not detected for plant densities and heights throughout the study (Table 1). Repeated measures analysis showed that undamaged, feeding-punctured, and total (Fig. 1A and B) cotton squares were not affected by the treatments at both locations. A treatment effect, however, was detected for abundances of oviposition-punctured squares at KSARC (F = 8.02; df = 2, 48; P = 0.0010) and Ansul (F = 16.15; df = 2, 48; $P < 0.0001$) with the fewest in the proactive treatment (Fig. 2A and B).

Bolls were more abundant in the proactive treatment than in the control (KSARC, F = 4.57; df = 2, 48; P = 0.0152; and Ansul, F = 6.44; df = 2, 48; P = 0.0033), but not in the standard treatment (Fig. 3A and B). At Ansul, the proactive treatment had fewer oviposition- (F = 3.95; df = 2, 48; P = 0.0258) and feeding (F = 4.96; df = 2, 48; P = 0.0110)-punctured bolls than the control. By the last sampling day, ≈46 and ≈64% of bolls per meter of row in the control had at least one oviposition puncture at KSARC and Ansul, respectively, but <0.2 fallen bolls per meter of furrow were found in any plot regardless of treatment.

There were smaller populations of beat bucket-collected adult boll weevils in the proactive treatment than in the standard treatment at KSARC (F = 4.02; df = 2, 48; P = 0.0237) (Fig. 4A) and compared with the standard treatment and control at Ansul (F = 4.89; df = 2, 48; P = 0.0117) (Fig. 4B).

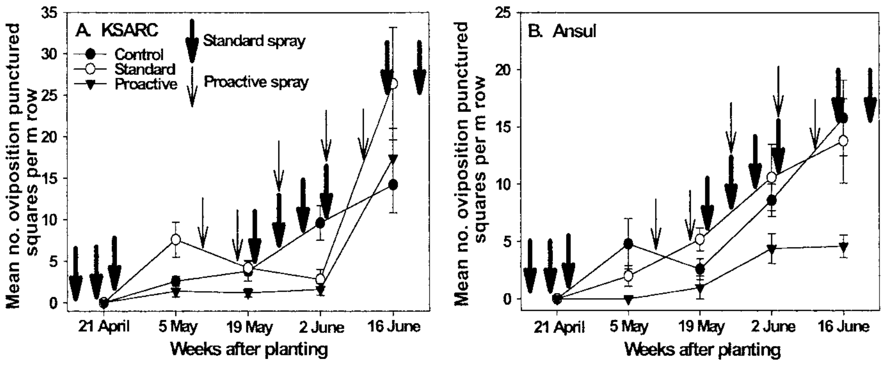

Fig. 2. Mean (±SE) numbers of oviposition-punctured squares per m of row in nontreated control plots and in standard and proactive treatment plots regimes at KSARC (A) and Ansul, Hidalgo County, Texas (B), 2004 (n = 5).

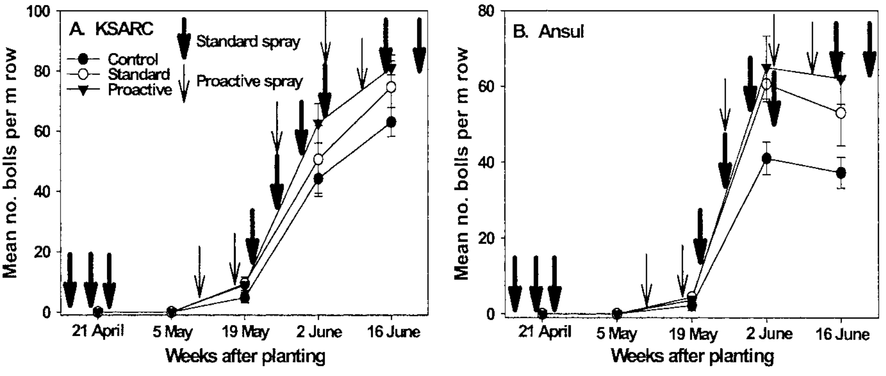

Fig. 3. Mean (±SE) numbers of bolls per meter of row in nontreated control plots and in standard and proactive insecticide treatment plots at KSARC (A) and Ansul, Hidalgo County, TX (B), 2004 (n = 5).

Total ginned lint yields were 46.4% (F = 11.62; df = 2, 11; P = 0.0086) and 56.2% (F = 29.08; df = 2, 14; P = 0.0002) greater in the proactive treatment than in the standard treatment at KSARC and Ansul, respectively, but differences between the standard treatment and the control were not detected (Table 2). The first harvest yielded 81–83% and 79–91% of the totals in all three treatments at KSARC and Ansul, respectively (Table 2). The first harvest at KSARC was 47 and 53% greater (F = 14.05; df = 2, 11; P = 0.0054) in the proactive treatment than in the standard treatment and the control, respectively (Table 2). Treatment effects were not detected for the second KSARC harvest. At Ansul, the first harvest of the proactive treatment yielded 48 and 142% more lint than the standard treatment and the control, respectively (F = 32.44; df = 2, 14; P = 0.0001) (Table 2). The second harvest of the proactive treatment at Ansul yielded 139% more than the standard treatment (F = 21.32; df = 2, 14; P = 0.0001) (Table 2).

At KSARC, net returns per hectare in the control and proactive treatment were 82 and 130%, respectively, greater (F = 23.69; df = 4, 19; $P < 0.0001$) than in the standard treatment (Fig. 5A). Net return from the proactive treatment at Ansul was 115 and 93% greater (F = 23.57; df = 4, 24; $P < 0.0001$) than from the standard treatment and control, respectively (Fig. 5B). Differences between net returns calculated for the two hypothetical standard treatment scenarios and the actual standard treatment were not detected at either location (Fig. 5A and B).

Discussion

Differences in square and boll populations, and numbers of both fruiting stages with oviposition and feeding punctures, were independent of plant density and height. Adult boll weevil populations in young cotton fields are low but increase rapidly when large squares become available (Showler 2004b, 2005; Showler et al. 2005). Newly emerged boll weevils fed large squares are associated with increased fecundity, oviposition, and numbers of gravid females compared with weevils fed match-head squares and postbloom (1–2-d-old), young (5–10-d-old), and old (3–5-wk-old) bolls (Showler 2004b). Under field conditions, boll weevils prefer to feed and oviposit on large squares than on other square sizes (Showler 2004b, 2005), which enhances the importance of large squares to boll weevil reproduction.

Preemptive insecticide application protects the nutritionally inferior and less-preferred early season pin-

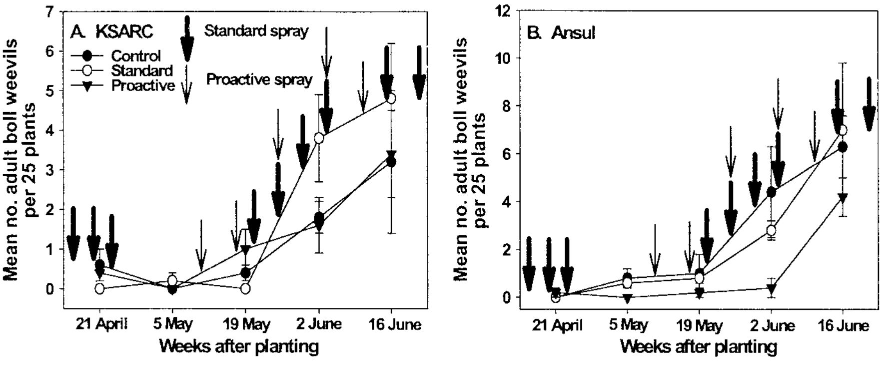

Fig. 4. Mean (±SE) numbers of adult boll weevil per 25 cotton plants collected by beat bucket in nontreated control plots and in standard and proactive insecticide treatment plots at KSARC (A) and Ansul, Hidalgo County, Texas (B), 2004 (n = 5).

Table 2. Mean (± SE) cotton lint yields from first and second harvests, 2004, Hidalgo County, Texas

Location[a]	Treatment	Harvest[b] First	Harvest[b] Second	Total
KSARC	Control	411.8 ± 17.4b	93.4 ± 8.3a	505.2 ± 21.3b
	Standard	427.5 ± 37.4b	92.0 ± 12.2a	519.5 ± 42.1b
	Proactive	629.4 ± 52.1a	131.4 ± 31.4a	760.8 ± 61.3a
Ansul	Control	365.0 ± 40.3c	96.4 ± 16.6ab	461.4 ± 59.3b
	Standard	596.2 ± 55.1b	59.6 ± 9.9b	655.8 ± 71.7b
	Proactive	882.0 ± 43.2a	142.8 ± 22.3a	1,024.8 ± 54.2a

[a] First and second harvests occurred on 6 and 14 July, respectively.
[b] KSARC replications, 4; Ansul replications, 5. Values within the same column and location followed by different letters are significantly different, ANOVA, Tukey's HSD.

head and match-head square sizes, for 9 to 10 d (assuming three sprays at 3-d intervals) (Showler and Scott 2005). Furthermore, preemptive sprays can only affect those few boll weevils (Showler 2005) exposed to the insecticides for the 9- to 10-d window (Showler and Scott 2005) before squares become large and weevil reproduction accelerates and populations build up. As a result, preemptive applications at the start of

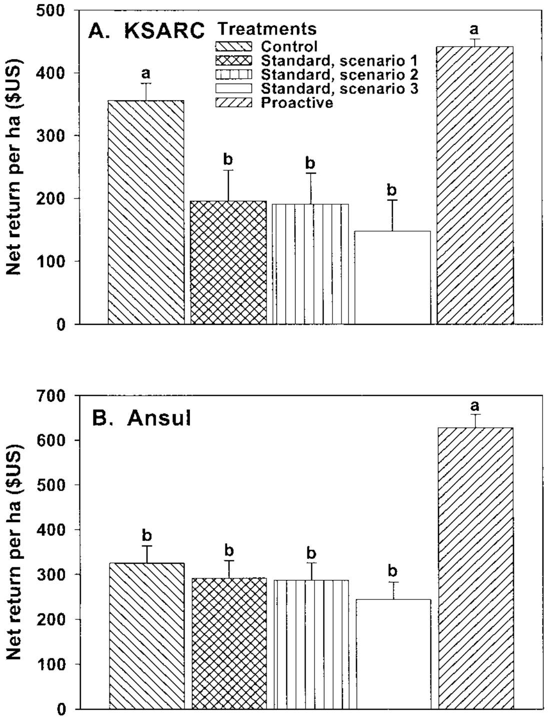

Fig. 5. Mean (±SE) economic return from nontreated control plots, standard treatment where all insecticide applications were by ground (scenario 1), hypothetical standard treatment where the first seven insecticide applications were by ground and the last two were by aircraft (scenario 2), hypothetical standard treatment where the first seven insecticide applications were by ground and the last two were by aircraft plus an additional two aerial applications (scenario 3), and proactive treatment plots at KSARC (A) ($n = 4$) and Ansul, Hidalgo County, Texas (B), 2004 ($n = 5$).

pinhead squaring do not affect numbers of later insecticide applications triggered by the 10% threshold or lint yields (Slosser 1988; Slosser et al. 1989, 1991; Showler 2004a).

Infested squares in the subtropics abscise after ≈6 d (Showler and Cantú 2005) when third instars have developed inside (Coackley et al. 1969). Although feeding and oviposition punctures were abundant on bolls, bolls are less vulnerable to boll weevil attack because even if one carpal is infested, the others can still produce lint (Walker et al. 1977; A.T.S., unpublished data) and because large bolls, often older and more difficult to penetrate than small bolls, are less preferred for oviposition than smaller the bolls (Baldwin et al. 1984, Greenberg et al. 2004). Also, pesticide application after cut-out (Guinn 1986, Cothren 1999), when squares are no longer initiated by the plant and bolls become the predominant fruiting stage, fails to suppress boll weevil infestations, whereas reproduction is accelerated (Showler 2004b). In addition, the value of the 10% intervention threshold is compromised by variability in total numbers of squares over time. Declining square populations coupled with surges in boll weevil populations increase the likelihood of triggering interventions based on randomly sampled squares, hence spraying increases to protect relatively few squares as the second harvest data indicate.

The proactive treatment is more effective at protecting yield than the standard treatment because it is timed to disrupt one to two generations of boll weevils that feed on reproduction-enhancing and highly vulnerable (because of the boll weevil oviposition preference) large squares when they are abundant (Showler 2004b). The 7-d interval between proactive applications includes the 3- to 4-d period during which commonly used insecticides for boll weevil control show lethal toxicity to adults in laboratory assays (Showler and Scott 2005). Boll weevil movement between squaring cotton fields is low (Guerra 1986) so much of the adult population 3 to 4 d after each application would likely be newly emerged and unable to reproduce until fed on squares or bolls (Showler 2004b). The interval between start of feeding on cotton fruit and oviposition is 5–7 d (Showler 2004b), but to be conservative we added only 3 to 4 d to the duration of insecticide effect; hence, the 7- to 8-d intervals between sprays. Because the spray interval was roughly estimated, shorter or longer intervals might further improve yield and net return.

Although beat bucket sampling collected adult boll weevils even in the proactive treatments, insecticide application could involve protection of squares by deterrence as well as by causing mortality. Under field conditions, an adult weevil contacts insecticide-treated leaves, stems, and bracts which might deter the weevil from gaining access to the bud inside. This could explain the relatively few oviposition-punctured squares in the proactive treatment while adult weevils were present.

Because bolls open through time, not simultaneously, treatment differences in numbers of bolls seemed smaller (open bolls were not counted) than yield differences. Negligible boll abscission indicates that bolls remained on the plants, opened, and the lint from undamaged carpals was harvested.

Our study demonstrates that protecting large squares with the proactive approach results in greater yields than when large squares are inadequately protected. In addition, the proactive treatment involved only five applications spanning one month in contrast to nine applications spanning four months in the standard treatment. Although the third and fourth proactive applications coincided with standard treatments sprays, the key to proaction is starting the spray series when large squares first develop and it is critically important to maintain protection of large squares until cut-out. The standard treatment failed to provide protection of large squares for the first nine days of large square formation and during the week before cut-out. The unprotected intervals allowed time for boll weevil feeding and oviposition on large squares.

Lint production was greatest in the proactive treatment at first harvest because it resulted from the open bolls that had been proactively protected as large squares. Although treatment differences for the second harvest at KSARC were not detected, yield in the proactive treatment was ≈40% greater than either of the other two treatments. The higher second-harvest yield in the proactive treatment at Ansul suggests that the duration of proactive treatment effects, ≈1 mo, provided substantial protection of large squares that developed near cut-out. The lack of statistical differences between the standard treatment and the control corroborates the idea that early and late season pesticide applications are inefficient. Our findings generally support the recommendation by Norman and Sparks (1998) for beginning chemical boll weevil control no earlier than one-third-grown squares.

Although this study was conducted in the subtropics, the underlying mechanism of the proactive approach should hold for other regions because it is reliant on the relationship of host plant growth and associated changes in nutritional quality relative to boll weevil reproduction and population dynamics during the growing season. Our experiments occurred at different locations during the same year because we were able to anticipate the 2005 arrival of the eradication program that requires applications of malathion in response to pheromone trap-based thresholds (Dickerson et al. 2001), in the Lower Rio Grande Valley during our planning. The locations were sufficiently far apart to reasonably discount population movement between fields during the growing season, and both locations had adult boll weevil populations typical of the Lower Rio Grande Valley and probably other subtropical cotton-growing areas within the boll weevil's distribution (Showler 2002, Showler et al. 2005).

Comparisons of net economic returns show that spraying for boll weevils by using the standard approach is less profitable under all three scenarios than the proactive approach. The difference resulted from the greater lint yields in the proactive treatment combined with the reduction of spray costs. Hypothetical use of aircraft for scenarios 2 and 3, being more expensive than spraying by ground, did not improve economic returns. This result also is expected because the aerial applications would occur after cut-out. Although mean lint yields were the same in the control and standard treatment plots at KSARC, no insecticide application costs were associated with the controls; therefore, economic return from the control was greater than from the standard treatment.

In-season protection gained from the proactive approach in cotton fields where boll weevils are not undergoing eradication (presently most of Mexico to Argentina) improves yield and economic return during the same season. Also, we suggest that proactive spraying can complement, or become part of, boll weevil eradication strategy that involves diapause sprays if it is implemented on an areawide basis.

Acknowledgments

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